

# Application of Temperature-Controlled Thermal Atomization for Printing Electronics in Space

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**Additive Manufacturing (AM) is a technology that builds three dimensional objects by adding material layer-upon-layer throughout the fabrication process. The Electrical, Electronic and Electromechanical (EEE) parts packaging group at Marshall Space Flight Center (MSFC) is investigating how various AM and 3D printing processes can be adapted to the microgravity environment of space to enable on demand manufacturing of electronics. The current state-of-the art processes for accomplishing the task of printing electronics through non-contact, direct-write means rely heavily on the process of atomization of liquid inks into fine aerosols to be delivered ultimately to a machine's print head and through its nozzle. As a result of cumulative International Space Station (ISS) research into the behaviors of fluids in zero-gravity, our experience leads us to conclude that the direct adaptation of conventional atomization processes will likely fall short and alternative approaches will need to be explored. In this report, we investigate the development of an alternative approach to atomizing electronic materials by way of thermal atomization, to be used in place of conventional aerosol generation and delivery processes for printing electronics in space.**

## I. Introduction

In addition to the numerous historically established technology accomplishments, there are four major research thrust areas of engineering and science developments at National Aeronautics and Space Administration (NASA) and Marshall Space Flight Center (MSFC) that draw the world's attention: Propulsion, Friction Stir Welding, CubeSats and Additive Manufacturing. In the field of Additive Manufacturing technology, the most current and established practices are implementing plastic Fused Deposition Modeling (FDM) and selective laser melting (SLM) based Additive Manufacturing processes for the generation of plastic and metal parts discretely. The Marshall team in collaboration with various other NASA centers is primarily focusing on using this AM technology to create functional electronic parts, giving birth to a focus area defined as Additive Electronics Manufacturing (AEM). The purpose of this area is to foster the capability to produce on-demand self-sustaining electronic/avionics parts that could be used for ISS research and/or onboard deep space exploration vehicles such as Space Launch System (SLS) and Orion. To accomplish this objective, Marshall is investigating, improving, and developing various terrestrial printing technologies and adapting them for use in microgravity. One of the most common practices utilized on electronics printers and spray deposition systems today is pneumatic or ultrasonic atomization. While these systems and processes reign supreme in a terrestrial environment, we predict that their performance will be limited due to lessons learned from ISS research over the years about the physics of fluids in microgravity. For the sake of this report Aerosol Jet Technology was investigated as a candidate process to baseline predictions going forward. Aerosol Jet® (AJ) printing is capable of printing fine, scalable, controlled depositions of conductive nano-particle fluid inks to create functional, geometrically complex, and robust avionics parts. In this report, we focus on the development of a novel approach for the aerosol mist generation of conductive ink and non-conductive ink utilizing a localized heating element through a conventional vaping device.

## II. The Description of Different Atomization Processes of Aerosol Jet® Printing

NASA MSFC has an Optomec Aerosol Jet® Deposition System 300 as shown in Figure 1. This machine is capable of generating aerosol mist that contains functional electronic material inks to deposit onto various substrates to produce functional electronic parts. Currently, there are two major methods within this system to generate aerosol mist: a pneumatic atomization process and an ultrasonic atomization process. In the text to follow, we will give a brief

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description of each atomization process. Furthermore, we will introduce the development of an alternative approach for mist generation of conductive and non-conductive ink through a localized heating element of a conventional vaping device.



**Figure 1.** Optomec Aerosol Jet® printer 300 (AJ 300) Series Located at MSFC

#### **(a) The Pneumatic Atomization Process method**

The NASA MSFC Aerosol Jet® printer (AJ 300) has traditionally used a pneumatic atomization process. The mist generation is accomplished by supplying external air pressure to an atomizing reservoir known as the pneumatic atomizer. Within the reservoir the device that performs the atomization functions by blowing the externally supplied air at high speed across the top of an open vertical channel that is submerged in the liquid. This high speed air blowing past the top of the submerged channel satisfies Bernoulli's principle creating a high velocity low pressure condition at the top of the channel and a low velocity high pressure condition at the bottom of the channel where the liquid ink exists. Fluid inks in this case flow from high to low pressure resulting in ink materials of low to high viscosity (0-1000 c.P.) to be drawn up the channel and atomized as they converge with the high velocity air moving across the top of the channel. The aerosol mist that is generated continues to expand until it completely fills the open volume within the atomizer reservoir and exits through the output port on to the next stage in printing. From this point in the process we can predict that under microgravity conditions of no hydrostatic pressure, buoyancy, and weight the fluid in the reservoir will not be contained and will not remain in continuous contact with the atomizer device. It is likely that the fluid will have no separation and exist as a single large body moving around within the open volume of the container. Potentially this single body of fluid could migrate and contact the output port and be pushed out of the reservoir completely from the rising air pressure and bypass atomization all together. This would decrease the overall continuous print consistency. Therefore, modification to this configuration or alternative means to atomize the liquid inks for delivery to the next stage in printing must be investigated.

#### **(b) The Ultrasonic Atomization Process method**

The process involving ultrasonic atomization for the AJ 300 is to utilize ultrasonic waves to aerosolize the conductive nanoparticle ink material. The limitation to this atomization process is the low viscosities of the ink material that could be used in the aerosolizing process. The typical viscosity value for ultrasonic atomization is usually 20 c.P. or less, which is fairly low in comparison to pneumatic atomization. In many aerospace printed electronics applications where the parts require higher concentration of metal content, this is not ideal.

In this atomization process, the conductive ink has been injected into an atomization vial and positioned over a transducer. The principle is that the transducer produces a sound wave that vibrates at ultrasonic frequencies. This high-energy ultrasonic wave then generates small perturbations to break up small droplets from the ink surface. For the best practice to generate efficient atomization, the use of a coupling fluid (usually temperature controlled deionized water) facilitates the transfer of ultrasonic energy from the transducer to the atomization vial in contact with the material. As the small aerosol droplets are ejected from the surface of the ink and fill the ultrasonic glass reservoir a glass tube provides a direct exit path from the vial to the print head for deposition. The configuration of this ultrasonic atomization system works well in laboratory environments on earth but presents fundamental challenges in microgravity. Again at this point we can predict that technical modification or alternative atomization techniques will need to be explored to enable this technology for use in microgravity.

### **III. The Development of an Alternative Atomization Process for Microgravity**

As a result of years of research in fluid science in both standard gravity and microgravity environments, basic phenomena can be used to anticipate the systems that will need to be developed to enable the production of fluid based electronics in space processing. One of the shared advantages that microgravity provides that is also available on earth is the principle of capillary action. In this work, capillary action is used as a means to wick/draw up the fluid ink from a sealed reservoir creating a more controllable delivery mechanism than the reservoirs mentioned previously. The ink can be trapped and packaged in a sealed reservoir that only allows the fluid to escape by means of capillary action through a custom designed wick of varying materials. In this proposed thermal atomization system the fluid is wicked out of the reservoir and delivered to the surface of metal coils to be atomized. The metal coils are wrapped around the wick and are heated by a temperature controlled power supply. When the temperature of the coils approach the boiling point of the solvent and liquid binders in the inks, they begin to atomize and expand freely, thereby creating an alternative thermal atomization process to generate mist for printing. This thermal wicking system serves as the foundation for the first step in enabling an alternative atomization process in microgravity.

#### **The Description of the device**

##### **(1) Power Supply**

We purchased a commercial product (SMOK OSUB 40W 1350mAh) as the power supply for the atomization process. The particular power supply model is shown in Figure 2. This is a OSUB Mod, which is a medium size power supply marketed for commercial vaping devices. In our experiments, the power usage was set to 27.5 watts. In addition, the supply has an adjustable temperature, micro USB port and OLED display for ergonomic purposes. The OSUB Mod supply has dimensions of 75 mm in depth, 25 mm in height and 54.5 mm in width. The temperature range is between 200 degrees and 600 degrees Fahrenheit and the voltage range is between 0.8V to 9.0V.



**Figure 2.** The Power Supply purchased for the thermal atomization process

##### **(2) Rebuildable Dripping Atomizer (RDA)**

The HCigar Legend V2 RDA was chosen and recommended by the vape shop experts as being ideal for this experiment. As seen in Figure 3, the RDA was chosen to provide an open platform where custom coils and wicks could be designed and built enabling virtually unlimited configurations of the atomizer setup.



**Figure 3.** The RDA purchased for the thermal atomization process

The RDA was manufactured from 304 stainless steel, Delrin insulator and O-rings, and solid copper pins. It has dimensions of 22 mm in depth, 46 mm in height and 22 mm in width. The total product weight for the RDA is 48 grams. It has a removable SS 510 drip tip and finned top design. It also has deep juice well and 510 threading connection. It processes adjustable 510 copper center screw and 22 mm overall diameter. Large air flow options allow for our dual coil setup and wide range air flow from low volume to massive intake volume, as in our case, was needed. Huge holes cross drilled through the post allow for flexible coil building, using a variety of wire gauges and creative building techniques. As can be seen in Figure 4, we build our two coils using Kanthal wires, carefully constructed so that the actual wires were not touching each other to avoid an electrical short circuit.



**Figure 4.** The Internal structure of the RDA for the thermal atomization process

### (3) The resistive coil



**Figure 5.** The conventional pre-made resistive coil for the RDA of the thermal atomization process

The design of the temperature control atomizing device involved optimizations of the following parameters: temperature coefficient of the wire, power consumption of the module, and coil resistance. The electrical temperature coefficient describes the change of resistance with respect to a temperature change. The higher the wire resistance temperature coefficient, the higher the accuracy of the temperature control. In our current experiment, the design concept for the development of a novel approach for mist generation of conductive ink and non-conductive ink through a localized heating element of a vaping device, we focused on using “Kanthal” wire, shown in Figure 6.

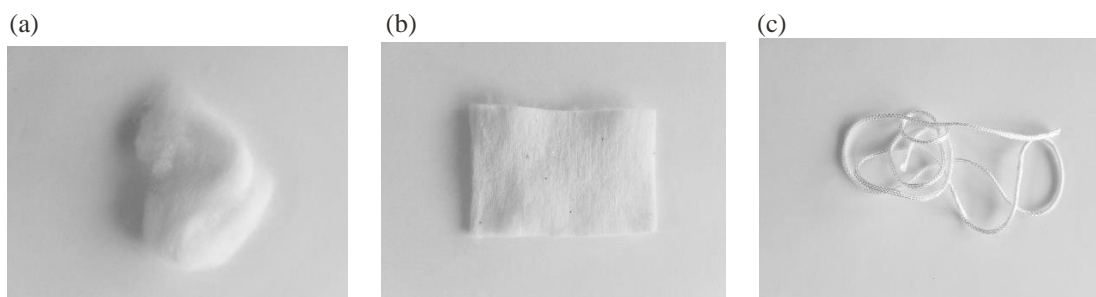


**Figure 6.** The Kanthal wire used to build a custom resistive coil of the RDA

We use Kanthal wire because it has low relative resistance change over increased temperature. This particular characteristic provides us a constant flow of aerosol. To enable an accurate temperature measurement, precise measurement of resistance is necessary. The power setting with temperature control enabled defines the maximum power that the temperature algorithm may apply to the coil. This is only true during the heat up phase at the beginning of the mist generation until the temperature has reached the set point. In general, in order to create a large amount of aerosol mist, the design concept adopted was to use thick wire and a high power setting.

#### (4) The wicking material

The wicking materials we experimented with are: Traditional cotton, Japanese Rayon cotton, and Silica, as illustrated in Figure 7 (a) (b) and (c). The silica wick is an amorphous material and has a dry burn characteristic. For the purpose of aerosol generation of the final conductive ink material, this wick proved superior to the conventional wicking material used for vaping, such as cotton. Silica wick is a mineral wick which does not break down like organic material. Our initial experiments using a cotton wick with conductive silver ink demonstrated that the cotton sintered with nanoparticle ink due to heat and became conductive, halting the atomization process.



**Figure 7.** (a) Traditional Cotton (b) Japanese Rayon cotton and (c) Silica Wick

#### (5) The fluid to be aerosolized

We experimented with thermal atomization of vegetable glycerin, polyimide and conductive silver ink as illustrated in Figure 8 (a) (b) and (c).



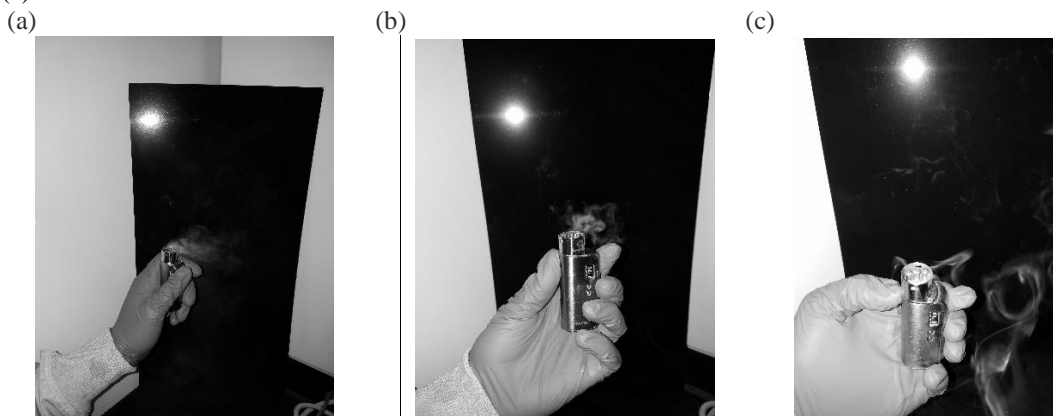
**Figure 8.** (a) Vegetable Glycerin (b) Nexolve® Polyimide and (c) Novacentrix® Conductive Ink

The boiling point for vegetable glycerin is between 188-190 degree Celsius. For the conventional vaping process, the chemical reaction is an incomplete combustion reaction. In a commercially available vaporizer, the concepts are to combine vegetable glycerin and flavor molecule into the vapor phase. In our experiment, we use USP-Kosher, food grade, non-GMO, palm derived pure vegetable glycerin with 1.7% minimum purity, and with no added flavor. The vapor phase serves as the aerosol droplet we are attempting generate. We use glycerin for a proof of concept to validate the functionality of our custom made Kanthal wire and silica wick. We then use the same device on polyimide fluid and finally conductive nanoparticle ink fluid. We begin this task by heating up a very high-temperature resistor coil. The general principle of thermal atomization is that heat transfer happens quickly and a large amount of liquid will be vaporized. One potential problem is that the high temperature heat source in the presence of oxygen can result in at least some of the liquid reaching combustion temperature instead of just vaporizing. Hydrocarbons in the vegetable glycerin molecule are partially oxidized. If the combustion process is complete, then only water and carbon dioxide will be the end product. When the combustion is incomplete, formaldehyde and acetaldehyde are formed.

We next attempted the thermal atomization of Polyimide using our thermal wick. The Polyimide material we use to atomize is Nexolve® CP1 Polyimide, a high performance material which has been widely used in display technology, space structures, thermal insulation and advanced composites. This material provides superior physical and electrical properties over a wide range of temperature and in a number of harsh environments. The polyimide liquid is shown in Figure 8 (b). The Nexolve® CP1 we are using is available in the form of continuous rolls, sprayable resin, castable resin, raw powder and optical film. We chose the sprayable resin with NMP solvent. Our polyimide CP1 Fluid has 6.06% solid loading and viscosity of 78 c.P. The conductive ink we used is from Novacentrix® Metalon® HPS 030-AE1. It is a water-based aerosol sprayable silver flake ink with viscosity between 130-180 c.P. and specific gravity of about 2.0. The silver content is 55% by weight. Figure 8 (c) shows Novacentrix® Metalon® HPS 030-AE1.

### (6) Experimental Results

We were able to generate the aerosol mist using all three of the candidate materials: vegetable glycerin, polyimide and conductive ink. Figure 9 illustrates the aerosol generation of (a) conventional vegetable glycerin (b) polyimide and (c) conductive ink.



**Figure 9.** Aerosol generation of (a) vegetable Glycerin (b) Nexolve® Polyimide and (c) Novacentrix® Conductive Ink

## III. Prediction of Fluid Behavior in Microgravity

Microgravity is defined as the acceleration conditions that exist on a reference frame in which the Earth's gravitational force is almost entirely balanced by the inertial force. The peculiar behavior of fluids in a microgravity environment motivate numerous Material Science and Life Science experiments in orbit. A number of basic phenomena may be identified which have a direct and/or indirect influence on the fluid behavior, and which could be exploited to improve a number of space processes (Monti and Savino 1997) as illustrated in following Table 1. [6]

Basic Phenomena in zero-g	Consequences in fluid phases	Utilization in space processing
No hydrostatic pressure	Large Interfaces, Large drops, Large liquid bridges Constant pressure in liquid specimens	Containerless processing, Undercooling in drops, Critical point experiment
No buoyancy	No separation between Phases or components	Metal synthesis, Miscibility gap
No natural convection (thermal/concentration)	Purely diffusive processes in the presence of temperature and/or concentration gradients	Growth from melts, from solution, as well as vapor, Precise measurement of fluid properties, Combustion, Dendrite growth
Reduced importance of gravitational effects	Separation effects due to: Marangoni flow, Thermal radiation forces Electromagnetic forces, wetting	Bubble/drops Marangoni migration, boiling, Bubble measurement, Floating zone refining
No weight		Large, soft crystal growth, large fractal structures, Arrogates of cosmic dust

**Table 1** The role of fluid behavior in physical science experiment [6]

## IV. Conclusion

We presume that ink reservoirs that are open and do not confine the liquid to stay in contact with the atomizer or fluid delivery mechanism will be ineffective in microgravity. The use of pressurized cartridges or capillary action based material delivery techniques will function as feasible alternatives. Further research is required to better understand the separation effects of liquid inks and their surface interactions during processes such as ultrasonic, pneumatic, and thermal atomization. Systems that direct and consolidate the mist after atomization will also need to be investigated to prove that the fundamental mechanisms they rely on are still functional in a microgravity setting. An overarching goal of this work is to serve as a starting point, forming a foundation for future applied research that will enable in-space manufacturing of electronics in a greater capacity.

The purpose of this project was not to rule out the possibility of using pneumatic and ultrasonic atomization based deposition systems in space, but to shed light on the need for alternative approaches to atomize and manipulate materials in future in-space manufacturing (ISM) processes. Enabling the capability to produce electronics on demand in space will reap enormous benefits that will enable NASA to explore in ways that were not previously possible. The potential new space-based electronics/avionics products will be in a class of their own and will serve to support the extraterrestrial technology markets of tomorrow. If these processes and technologies are supported in the early stages the potential payoff could enable a standard of living in space and on earth that would support longer duration deep space exploration, habitation, and sustainability.

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## References

- <sup>1</sup>Snyder, M. P., Dunn, J. J., Gonzales, E. G., “Effect of Microgravity on Extrusion Based Additive Manufacturing”, *American Institute of Aeronautics and Astronautics Space 2013 Conference and Exposition*, San Diego, CA. September 10-12, 2013.
- <sup>2</sup>Sunol, F., Gonzalez-Cinca, R., Liquid Jet Breakup and Subsequent Droplet Dynamics Under Normal Gravity and in Microgravity Conditions. *Physics of Fluids* 2, 077102. (2015).
- <sup>3</sup>Gibson, I., *Additive Manufacturing Technologies*, 2<sup>nd</sup> edition, Springer, New York, 2015.
- <sup>4</sup>Prater, T. J., Bean, Q. A., Beshears, R. D., Rolin, T. D., Werkheiser, N. J., Ordonez, E. A., Ryan, R. M., Ledbetter, F. E., “Summary Report on Phase I Results From 3D Printing in Zero-G Technology Demonstration Mission, Volume I, NASA/TP-2016-219101, Marshall Space Flight Center, Huntsville, Alabama.
- <sup>5</sup>Aerosol Jet and Optomec are trademark of Optomec, Inc.
- <sup>6</sup>Monti, R., *Physics of Fluid in Microgravity*, Taylor and Francis, New York, 2001.
- <sup>7</sup>Lappa, M., *Fluids, Materials & Microgravity-Numerical Techniques and Insights into Physics*, Elsevier, Oxford, 2004.